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Proposed criterion for fatigue strengthening of riveted bridge girders

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Abstract

Most existing guidelines and recommendations for the fatigue design of riveted members are not considering the effect of stress ratio on the constant amplitude fatigue limit (CAFL). However, fatigue test data show that there is a substantial influence of the stress ratio on the CAFL. In this study, a simple fatigue design criterion for riveted members is proposed taking into account the effect of stress ratio. The applied method is based on the constant life diagram (CLD) methodology. The accuracy of the proposed design criterion has been verified using existing test data in the literature. This consideration enables the application of an effective solution for prevention of fatigue failure in riveted members, namely the application of prestressed retrofitting systems, which results in a reduction of the stress ratio. A procedure is therefore presented for the fatigue design of the riveted members strengthened with prestressed and non-prestressed retrofitting systems subjected to constant and variable amplitude loadings. The proposed design procedure is then used in a numerical example to determine the prestressing force and the section modulus required for prevention of fatigue cracking in both the prestressed and non-prestressed retrofitting systems.

Keywords: Riveted Structures; Retrofitting; Fatigue design; Stress ratio; Prestressed strengthening; Constant life diagram (CLD)

1. Introduction

Load carrying capacity of old steel bridges is a worldwide concern. In Europe, nearly 70% of all metallic bridges are more than 50 years old, and 30% are over 100 years old (Bien et al., 2007). Many of these bridges contain hot

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riveted joints. similar situations exist in the US (Karbhari and Shulley, 1995), Japan (Yamada et al., 2002) and Australia (IEAust, 1999).

Fatigue is often a major problem in aging riveted steel bridges, mainly railway ones, accounting for the majority of steel bridges built before the middle of the last century all over the world. The increasing service loads, and, the harsh environmental conditions resulting in corrosion make hot riveted joints in bridges even more prone to fatigue cracks (Cremona et al., 2007).

Strengthening of old structures is of interest to the owners, rather than replacement of the whole structures. For the riveted members, traditionally, different retrofitting solutions have been proposed: replacement of the rivets with high-strength pre-tensioned bolts (Al-Emrani, 2002, Baker and Kulak, 1985, Reemsnyder, 1975), welding additional elements, stop holes (Fisher et al., 1980) and softening the riveted connections by removing some rivets (Bowman, 2012). However, experimental studies (Roeder et al., 2005) show that the methods such as stop holes and replacement of the rivets with high-strength bolts only delay the crack propagation, and new cracks are likely to occur at other locations. In addition, welding of old steels may introduce other problems such as lamellar tearing and it may lead to additional fatigue cracks prone locations at the welds.. Therefore, many of these methods for strengthening the riveted members are not capable of permanently eliminating the possibility of initiation and propagation of fatigue cracks in riveted members.

Application of non-prestressed bonded retrofitting systems by new materials, such as Carbon Fiber-Reinforced Polymers (CFRPs), has been studied as an attractive method for strengthening the metallic structures (Mertz, 1996, Schnerch et al., 2007).

From the fatigue point of view, in order to practically eliminate the problem (i.e. achieving infinite fatigue life) in an element, the stress range, the mean stress or both have to be reduced below a certain threshold (Shigley, 2011). Defining the stress ratio R, as the ratio between minimum and maximum stresses, the reduction of mean stress of the cycles leads to the reduction of stress ratio as long as the maximum stress is a tensile stress.

Based on Eurocode EN 1993-1-9 (2005), for constant amplitude loadings, in order to achieve the infinite fatigue life, the stress range has to be lower than the Constant Amplitude Fatigue Limit (CAFL), but the S-N curves for different categories presented in Eurocode EN 1993-1-9 don't take into account the effect of stress ratio, R, on the fatigue resistance when $0 \leq R < 1$ because they conservatively assume high tensile self-equilibrating stresses in the members. However, previous studies ((Taras and Greiner, 2010) and (Maljaars et al., 2019)) have revealed that the fatigue resistance of hot riveted joints also depends on the mean stress, and as a result, on the stress ratio.

Due to the big dimensions of the members in many old riveted structures, addition of non-prestressed bonded materials to the existing members doesn't significantly reduce the stress range. Therefore, prestressed retrofitting systems have been introduced, making it possible to reduce both the stress range and the mean stress (Ghafoori and Motavalli, 2015, Ghafoori and Motavalli, 2016, Ghafoori et al., 2015b, Ghafoori et al., 2015a, Ghafoori et al., 2015c). As these solutions mainly rely on reducing the mean stress of the cycles, thus, S-N curves proposed in Eurocode EN 1993-1-9 are not capable of taking into account the positive effect of prestressed retrofitting systems when $0 < R < 1$.

In this study, the Constant Life Diagram (CLD) method (Shigley, 2011) is used for the prediction of fatigue crack in riveted metallic members in order to consider the effect of stress ratio on the value of CAFL. The CLD method is a local approach in which the stresses in the hotspots are used for prediction of fatigue crack initiation, considering the effect of the material properties and geometry; i.e. stress raisers such as notch effect.

In the current study, first the formulations presented in different codes for fatigue design of riveted members, as well as the proposed method, are explained. Second, the capability of the proposed criterion predicting the CAFL in riveted members is evaluated through comparison with the experimental data collected from the literature.

Then, a fatigue design procedure is introduced for the riveted members strengthened with prestressed and non-prestressed retrofitting systems, subjected to constant and variable amplitude loadings, with the inclusion of stress ratio effect. This design procedure is applied in a numerical example, and respectively, the required prestressing force and the section modulus in prestressed and non-prestressed strengthening systems are determined.

2. Prediction of CAFL in riveted members

In this section, the formulations for the prediction of CAFL, based on different codes and the proposed criterion, are presented.

2.1. Eurocode

Based on the recommendation for Eurocode, category EC71, which is accounted as a lower bound for fatigue strength of riveted members, is used for the design check of riveted members (Kuehn et al., 2008). EC71 stands for the fatigue strength (allowable stress range) is equal to 71 MPa at 2 million cycles.

The CAFL value, $\Delta\sigma_{\mathrm{D}}$, is considered to be constant for $R \geq 0$. For $R < 0$, in which both tension and compression are present in the cycles, 60 percent of the compressive portion of the stress range is added to the whole tensile portion of the cycles in case of non-welded details such as riveted joints (or stress relieved details). Therefore, for $R < 0$, the effective stress range is:

$$\Delta\sigma_{\mathrm{D},R<0} = \sigma_{\max} - 0.6\sigma_{\min} \tag{1}$$

The relationship between the maximum and the minimum stresses, $\sigma_{\max}$ and, $\sigma_{\min}$, respectively, with the stress range the stress ratio $R = \sigma_{\min} / \sigma_{\max}$ is given in Eq. (2):

$$\sigma_{\max} = \frac{1}{1-R}\Delta\sigma \text{ and } \sigma_{\min} = \frac{R}{1-R}\Delta\sigma \tag{2}$$

Where $\Delta\sigma$ is the applied stress range: $\Delta\sigma = \sigma_{\max} - \sigma_{\min}$. By substituting Eq. (2) in Eq. (1), the allowable stress range for different stress ratios proposed by Eurocode (2005) is given in Eq. (3):

- For 0≤R<1: $\Delta\sigma = \Delta\sigma_{\mathrm{D}}$ (3-a)
- For $R < 0$: $\Delta\sigma = f(R)\Delta\sigma_{\mathrm{D}}$ with $f(R) = 1 - R/(1-0.6R)$ (3-b)

The value of $\Delta\sigma_{\mathrm{D}}$ is equal to 52 MPa for the category EC71.

2.2. German Standard DIN and Austrian standard ÖNORM

The effect of *R* ratio has been also considered in German standard DIN and Austrian standard ÖNORM (Taras and Greiner, 2010). In their identical proposed formulations, the fatigue resistance $\Delta\sigma_{\mathrm{D}}(R)$ is equal to the product of a stress ratio function $f(R)$ and the fatigue resistance when $R = 0$, i.e. $\Delta\sigma_{\mathrm{D},R=0}$, as given in Eq. (4):

$$\Delta\sigma_{\mathrm{D}}(R) = f(R) \times \Delta\sigma_{\mathrm{D},R=0} \tag{4}$$

The value of $f(R)$ is determined with the following equations:

For wrought iron and mild steel before 1900

- For 0 ≤ R < 1: $f(R) = 1 - R/(1-0.75R)$
- For $-1 \leq R < 0$: $f(R) = 1 - R/(1-0.7R)$

(5-a)

For mild steel after 1900

- For 0≤ R <1: $f(R) = (1-R)/(1-0.6R)$
- For $-1 \leq R < 0$: $f(R) = (1-R)/(1-0.4R)$

(5-b)

The main difference with Eq. (3) is that a penalty is provided for 0≤ R <1 in Eq. (5). Unfortunately, it is not clear to the authors how the stress ratio functions in Eq. (5) have been obtained; namely, is it either supported by any experimental data or by a specific analytical approach?

2.3. Proposed formulations

In this section, the methodology and formulations for estimating the CAFL value, considering the effect of *R* ratio is described. The proposed methodology is based on the CLD approach (Shigley, 2011). In the CLD approach, in addition to the stress amplitude σ_a, the mean stress σ_m is considered for the prediction of crack initiation. The stress amplitude and the mean stress are defined as follows:

$$\sigma_a = (\sigma_{\max} - \sigma_{\min})/2, \sigma_m = (\sigma_{\max} + \sigma_{\min})/2 \tag{6}$$

Based on Johnson's criterion (Johnson, 1897, Johnson, 1899), the stress amplitude below which no fatigue crack is expected to initiate is related to the mean stress and the ultimate tensile strength S_{ut}, with the following relationship:

$$\frac{\sigma_a}{S_{ut}/3}+\frac{\sigma_m}{S_{ut}}=1 \tag{7}$$

It is worth mentioning that Johnson's criterion has been selected because this criterion is used for the design when minimum information about the metal is available; i.e. only the material tensile strength is needed (Ghafoori et al., 2015a). Combining Eq. (2), (6) and (7), along with the fact that $2\sigma_a = \Delta\sigma$, the following relationship is obtained:

$$\sigma_a=\frac{S_{ut}}{4}\left(\frac{1-R}{1-0.5R}\right) \tag{8}$$

Eq. (7) and (8) apply to a uniformly stressed member section. In a riveted joint, however, the stress distribution is not uniform, i.e. the stress near the rivet hole (the hot-spot) is significantly larger as compared to the average stress over the net section, the latter referred to as the nominal stress. In this case, Eq. (7) would apply to the hot-spot, with some correction introduced later.

Engineers in design, however, use the nominal stress range $\Delta\sigma$ rather than stress amplitude in the nominal σ_a, or hot-spot $\sigma_{a,\text{hot-spot}}$. The nominal stress is calculated based on the elastic cross-section analysis of the net section. Therefore, the fatigue factor k_f is used to transform from the stress amplitude obtained by the CLD method, as a local approach, to the nominal stress range, as given in Eq. (9):

$$2\times\sigma_{a,\text{hot-spot}}=\Delta\sigma_{\text{nominal}}\times k_f \tag{9}$$

Combining Eq. (8) and (9), the nominal stress range $\Delta\sigma$, is obtained as a function of stress ratio and material tensile strength, as given in Eq. (10):

$$\Delta\sigma=\frac{S_{ut}}{2k_f}\times f(R)\ \text{with}\ f(R)=(1-R)/(1-0.5R) \tag{10-a}$$

Form Eq. (10), the value of fatigue strength when $R=0$ is equal to $S_{ut}/2k_f$ .It is worth mentioning that the stress ratio function $f(R)$ obtained by Eq. (10) is somewhat similar to that of Eq. (3-b) for R < 0, and Eq. (5). However, the value of CAFL at $R=0$ proposed in this study is different from those proposed in different codes. In the proposed model, the value of CAFL, in addition to the stress ratio, is dependent on the material strength as well as the fatigue factor k_f .

The value of fatigue factor k_f is dependent on the notch sensitivity factor q and the stress concentration factor (SCF) k_t, with the following relationship (Shigley, 2011):

$$k_f=1+q(k_t-1) \tag{11}$$

The notch sensitivity factor q is normally between zero and unity, and is defined as (Shigley, 2011):

$$q=1/(1+\sqrt{a}/\sqrt{r}) \tag{12}$$

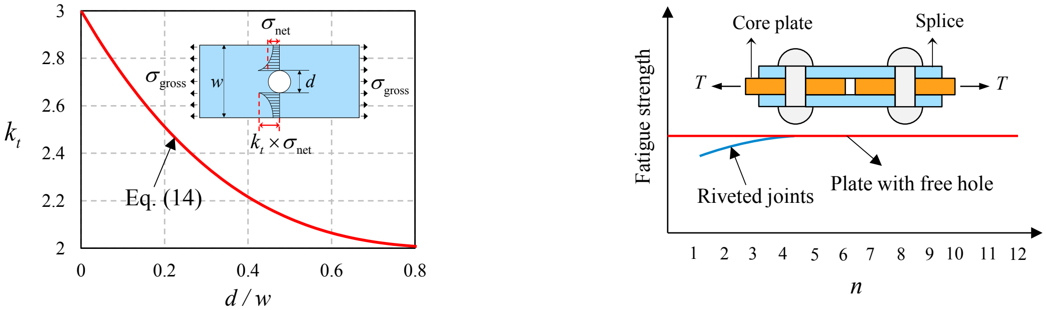
Where r is the radius of the notch, and, $\sqrt{a}$ is the Neuber constant, which is obtained by Eq. (13) for steel (Shigley, 2011) as given below:

$$\sqrt{a(\text{mm})}=174/S_{ut}(\text{MPa}) \tag{13}$$

The value of the notch sensitivity factor for wrought irons is $q=1$, and for cast-iron, ranges between 0 and 0.2. For further information, see (Shigley, 2011) and (Ghafoori et al., 2015b).

As shown in Fig. 1-a, the SCF, k_t, is dependent on the geometry of the member consisting of a plate, with the hole diameter of d in the center, and the width of w. The value of k_t, based on the calculations of Howland (Howland, 1930), was approximated by Heywood (Heywood, 1962) as given in Eq. (14):

$$k_t=2+\left(1-\frac{d}{w}\right)^3 \tag{14}$$



(a) (b)

Fig. 1. (a) SCF for a plate with a hole in center, and, (b) Fatigue strength of riveted joint with different number of rivets in a line

Based on Eq. (11) and (12), k_t is greater than k_f. In fact, the notch sensitivity factor q, is used to reduce the SCF k_t to a lower value of fatigue factor k_f. The reason is that the initiation of a fatigue crack depends on the stress range acting on a specific volume of a material and not on a single point, and thus, is influenced by the stress gradient and the material grain size. The notch sensitivity factor q, accounts for the stress gradient by considering the radius of the notch r, and, for the material grain size through the Neuber constant.

2.4. Applicability of the proposed methodology in fatigue design of riveted members

It is important to notice that Eq. (14) has been suggested for a plate with a free hole in center, while the riveted structures have multiple holes filled with rivets. In riveted joints, the applied load is transmitted through both bearing and friction. Yin et al. (Yin et al., 1982) have proposed the simplified model for calculating the effective stress concentration factor k_{eff}, in riveted joints, given in Eq. (15):

$$k_{\text{eff}} = \frac{1}{n} k_{\text{bearing}} + \frac{n-1}{n} k_{\text{hole}} \tag{15}$$

Where n is number of rivets in a line, k_{bearing} is the SCF for a lap joint with only one non-pre-tensioned rivet ($k_{\text{bearing}} \geq 5$), and k_{hole} is the SCF for a plate with a free hole. Based on Eq. (15), when the number of rivets in a line increases, the value of k_{eff} tends towards k_{hole} (Akesson, 2010, Yin et al., 1982) . Based on the experiments by Yin et al. (Yin et al., 1982), for a riveted joint with 4 rivets in a line, the fatigue strength approaches that of a plate with an empty hole.

This model is also supported by the experimental results presented in (Yin et al., 1982), where several lap joints, with different number of rivets in a line, were subjected to fatigue loadings. It was concluded that the fatigue strength of riveted joints with four or more rivets in a line is equal to that of a plate with a free hole, as shown in Fig. 1-b. As there are usually several rivets in a line in riveted members, the formulations developed for a plate with a free hole is applicable to a riveted member with multiple lines of rivets (more than 4).

In addition, in many experimental studies, the riveted beams are tested in a four-point bending set-up, in which the rivets in the constant moment region (where usually fatigue cracks are found) are not subjected to shear. Thus, the above-mentioned formula for a plate with a free hole is directly applicable.

2.5. Lower bound for CAFL based on proposed criterion

According to Eq. (10), the value of CAFL is dependent of the material tensile strength and the geometry of the member. In order to consider both of the parameters, the coefficient α is defined as:

$$\alpha = \frac{S_{\text{ut}}}{k_f} \tag{16}$$

Therefore, Eq. (10) is rewritten as:

$$\Delta\sigma = \frac{\alpha}{2} \times \left(\frac{1-R}{1-0.5R}\right) \tag{17}$$

Table 1 summarizes the values of α obtained based on the average material tensile strength and geometry of the riveted elements in different studies including the number of rivets in a line. Based on Table 1, the minimum value of α is equal to 144, which can be used for the fatigue design of riveted members as a lower bound of CAFL. Using this value for α results in the lowest line for the CAFL. Therefore, the simple equation proposed for the design is:

$$\Delta\sigma_{\mathrm{D}} = 72\times\left(\frac{1-R}{1-0.5R}\right) \tag{18}$$

Table 1. The value of α in different experimental studies

Study	d (mm)	w (mm)	Number of rivets in a line	S_{ut} (MPa)	k_f	α(MPa)
Bruhwiler et al. (1990)	21	125	24	388	2.38	163
	19	70	12	344	2.39	144
Akesson (2010) and Al-Emrani (2002)	20	115	22	391.8	2.37	165.3
Baker and Kulak (1985)	21	82.5	4	390	2.25	173.3
	19	89	12	390	2.3	169.6
Fisher et al. (1987)	22	177.5	>> 4	385	2.47	155.8
	22	152	>> 4	385	2.43	158.4
Reemsnyder (1975)	19	110.4	>> 4	448	2.39	187.4
Graf (1935)	20	79	4	572	2.29	249.8
Ghafoori et al. (2015b)	23	115	One free hole	562	2.38	236.1

3. Comparison of the proposed criterion with the existing experimental data

Available experimental results from the sources of Table 1 are plotted in Fig. 2 altogether. The results have been collected from the experimental studies in which the fatigue cracks have initiated from the rivet holes, and not from the rivets themselves. In this figure, the criterion proposed by DIN and ÖNORM, Eurocode (2005) and the one proposed in this study are plotted using Eq. (3), Eq. (5-b) and Eq. (18), respectively.

In different studies, different number of cycles has been assumed for being run-out. The minimum number of cycles considered was 7 million (Brühwiler et al., 1990), While in some others the fatigue tests were stopped after 20 million cycles (Akesson, 2010, Brühwiler et al., 1990). It is worth mentioning that for each test series, the CAFL line can be plotted using Eq. (10). The proposed criterion in Fig. 2 is the lowest line obtained by Eq. (18).

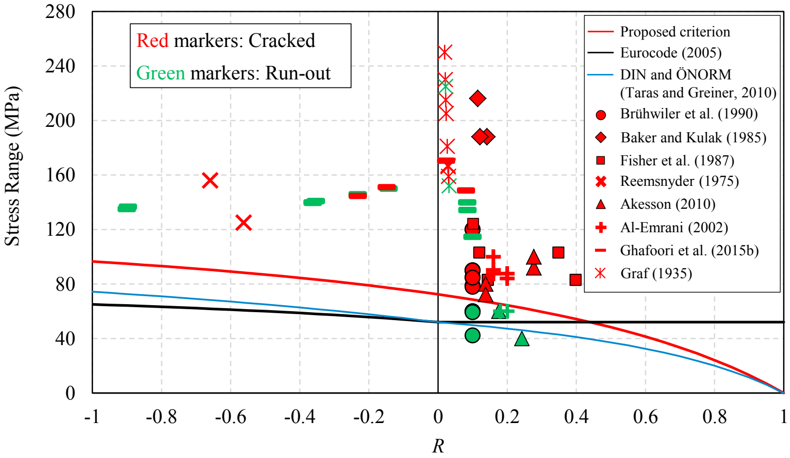


Fig. 2. Stress range versus stress ratio for different experimental studies

Fig. 2 shows that the proposed criterion can predict the limit between fatigue failure and run-outs fairly well. On the other hand, the criterion proposed by DIN and ÖNORM as well as Eurocode (2005) are conservative in the stress ratios smaller than around 0.4.

However, in the majority of the previous studies, the stress ratio was between 0.1 and 0.3. To the best of authors' knowledge, there are only two studies with $R < 0$, and, with 4 or more rows of rivets (Ghafoori et al., 2015b, Reemsnyder, 1975). Therefore, the accuracy of the different criteria in the region with $R < 0$ needs to be investigated by further experimental studies in the future. Especially, when prestressed strengthening systems are applied, as described in section 4, the stress ratio may become negative. It clarifies the need for verification of the mentioned criteria for $R < 0$.

It must be highlighted that the CAFL value derived is a first estimate that seems to work reasonable for the data considered in this study, but that it should not be used as a general value for every configuration of a riveted joints without further evaluation, e.g. single lap joints, joints with a small number of rivet rows, and joints with corrosion.

4. Application of the proposed method for strengthening the riveted members

In this section, the capabilities of the proposed criterion and Eurocode (2005) to take into account the effect of strengthening on riveted members are compared. In addition, a design procedure is applied for members strengthened with prestressed and non-prestressed retrofitting systems subjected to constant and variable amplitude loadings.

As shown in Fig. 3, the red point, which is a result of the tests done by Brühwiler et al. (1990), is beyond the CAFL of 52 MPa, suggested by Eurocode EN 1993-1-9 (2005) and the proposed criterion. In order to bring the point into the safe zone (below the proposed curve), i.e. the zone with the infinitive fatigue life, the riveted member has to be strengthened, either with prestressed (with the main effect path 1) or non-prestressed (path 2) systems which are described in the following sections.

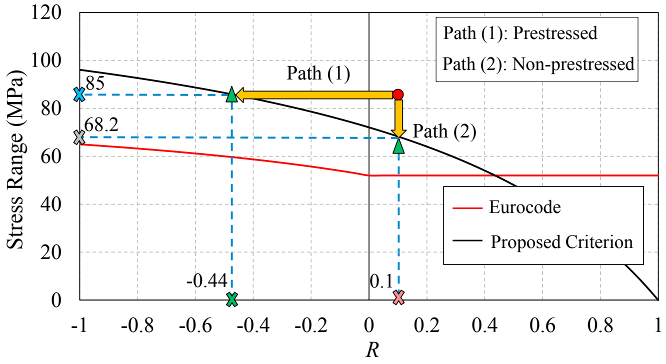


Fig. 3. Effect of strengthening for prestressed and non-prestressed retrofitting systems

4.1. Prestressed retrofitting systems

Consider a riveted beam, with the dimensions shown in Fig. 4-a (Brühwiler et al., 1990), that is subjected to cyclic external loading of ΔF . This beam is be strengthened with a prestressed strengthening system in this section.

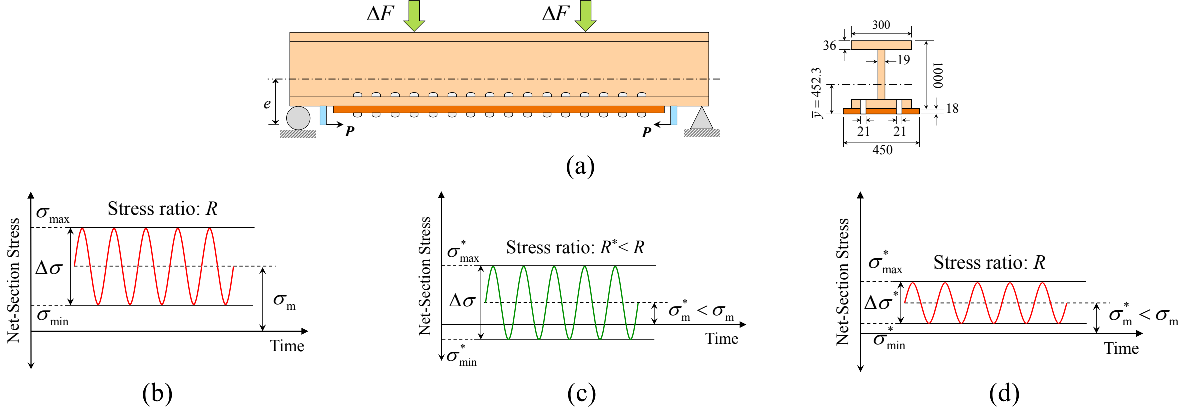


Fig.4. Strengthening a riveted member with prestressed and non-prestressed systems; (a) Configuration of the riveted beam (Brühwiler et al., 1990), (b) Net-section stress before prestressing, (c) Net-section stress after prestressing, (d) Net-section stress after strengthening with non-prestressed system

Application of a prestressed retrofitting system for the strengthening the span of the girders with big dimensions doesn't usually change the stress range significantly (Ghafoori and Motavalli, 2015, Ghafoori and Motavalli, 2016, Ghafoori et al., 2015c), while it decreases the stress ratio as shown in Fig. 4-b and c. In other words, the mean stress σ_{m} is reduced to the lower value of σ_{m}^{*} as depicted in this figure.

The goal is to obtain the minimum prestressing force *P*, required for a system with the eccentricity of *e* (see Fig. 4-a), according to the proposed criterion. As shown in Fig. 3, before strengthening, the stress ratio is *R*. Application of prestressing force reduces the stress ratio to *R**, with the stress range remaining constant (path (1) in Fig. 3). Using Eq. (10), the reduced stress ratio *R**, corresponding to which is on the curve of the proposed criterion (see Fig. 8), is obtained by Eq. (19):

$$R^{*}=1-\frac{\Delta\sigma}{\frac{S_{ut}}{k_{f}}-\Delta\sigma} \tag{19}$$

The maximum stress level $\sigma^{*}{}_{\max}$ after application of prestressing force (see Fig. 4-c), according to Eq. (2) and Eq. (19), is obtained by the following equation:

$$\sigma^{*}{}_{\max}=\frac{S_{ut}}{k_{f}}-\Delta\sigma \tag{20}$$

Cross-section analysis after application of prestressing force of *P* implies that:

$$\sigma^{*}{}_{\max}=\frac{M_{\max}}{S_{\mathrm{net}}}-P\left(\frac{e}{S_{\mathrm{net}}}+\frac{1}{A_{\mathrm{net}}}\right) \tag{21}$$

Where $M_{\max}$ is the maximum bending moment due to the external load, and, S_{net} and A_{net} are the section modulus and the net section area, respectively. Considering the fact that the stress range $\Delta\sigma$, and the stress ratio before strengthening, *R*, have the following relationship with the first term of the right side of Eq. (21):

$$\frac{M_{\max}}{S_{\mathrm{net}}}=\frac{\Delta\sigma}{1-R} \tag{22}$$

Therefore, using Eq. (20), (21), (22) and (16), the prestressing force *P* is obtained by Eq. (23):

$$P>\left(\frac{2-R}{1-R}\Delta\sigma-\alpha\right)/\left(\frac{e}{S_{\mathrm{net}}}+\frac{1}{A_{\mathrm{net}}}\right) \tag{23}$$

Using the value of $\alpha=144$ (see Table 1), for the design purpose, the required prestressing force is only dependent on the stress ratio of the applied load as well as the section properties of the riveted member. For the beam shown in Fig. 4-a, which is subjected to a constant amplitude loading with *R*=0.1 (see Fig. 3), the required prestressing force is: $P>723\ \mathrm{kN}$, using Eq. (23).

The important point is that according to the Eurocode criterion, with such stress range and stress ratio, it is nearly impossible to prevent fatigue crack in this riveted member, shown in Fig. 3, since it only accounts for the effect of *R* ratio for R < 0.

4.2. Non-prestressed retrofitting systems

When non-prestressed strengthening systems are used, the stiffness of the structural members increases, resulting in reduction of the stress ranges. Thus, as shown in Fig. 4-d, the nominal stress range decreases. If the dead load of the riveted member is negligible compared to the superimposed live loads, the stress ratio can be assumed to remain constant. Therefore, the points which are beyond the fatigue limit curves, shown in Fig. 3, follow the path (2), as a result of the strengthening.

In order to determine the additional stiffness required to bring the point from above the CAFL to below it, it is essential to know which failure criterion is selected; i.e. either the curve proposed in this study or that presented in Eurocode EN 1993-1-9 (2005) (see Fig. 3).

In order to be inside of the zone of infinite fatigue life based on the proposed criterion, the maximum stress range in the beam has to be reduced from $\Delta\sigma$ to at least $\Delta\sigma^{*}$ (see Fig. 3). Using Eq. (17), along with the fact that $\Delta\sigma^{*}\times S_{\mathrm{net}}^{*}=\Delta\sigma\times S_{\mathrm{net}}$, the minimum section modulus required for reducing the stress range from $\Delta\sigma$ to $\Delta\sigma^{*}$, is obtained as:

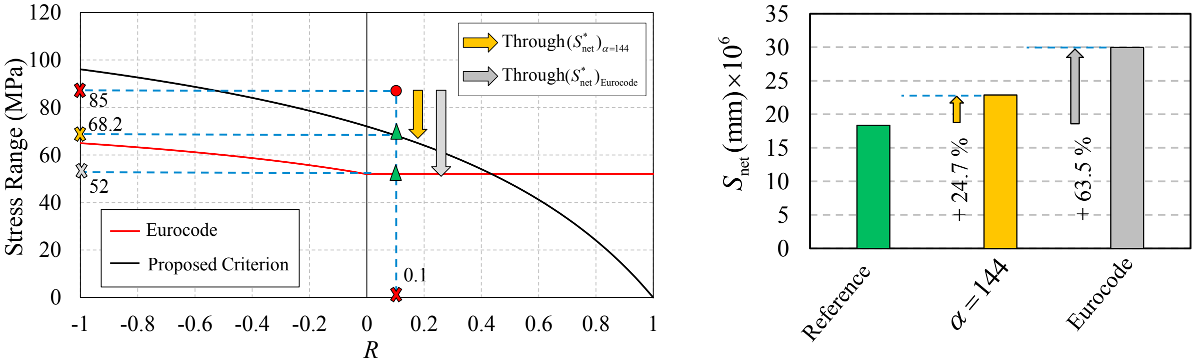
$$S^{*}_{\mathrm{net}} = \frac{2\Delta\sigma}{\alpha}\left(\frac{1-0.5R}{1-R}\right)\times S_{\mathrm{net}} \tag{24}$$

“Where S_{net} refers to the section modulus at the location of the rivets. In order to bring the point below the threshold, according to Eurocode EN 1993-1-9 (2005), the minimum required section modulus is:

$$S^{*}_{\mathrm{net}} = \frac{\Delta\sigma\ (\mathrm{MPa})}{52}\times S_{\mathrm{net}} \tag{25}$$

It is important to notice to this fact that in Eq. (24) and (25) it is assumed that a complete bond exists between the riveted member and the added material for strengthening. In the cases with unbonded non-prestressed strengthening systems, the value of S^{*}_{net} has to be calculated by fulfilling the compatibility equations.

As a numerical example, the beam shown in Fig. 4-a, and, subjected to the constant amplitude cyclic loading with the stress range $\Delta\sigma = 85$ MPa and stress ratio R=0.1 (see Fig. 3) is considered. This beam is going to be strengthened with a steel plate which is bonded to bottom flange of the beam. Using Eq. (24) and Eq. (25), the required section modulus to transfer into the safe zone based the proposed criterion and also Eurocode EN 1993-1-9 (2005) are obtained, as given in Fig. 5.



(a) Strengthening effect (b) The Min. required section modulus

Fig. 5. The required section modulus for the beam strengthened with non-prestressed retrofitting system

As it is shown in Fig. 5, in order to bring the point from the risky zone into the safe zone, the stress range should be reduced much more when Eurocode EN 1993-1-9 criterion is used; because the fatigue limit proposed by Eurocode is more conservative. Therefore, the minimum required section modulus, based on Eurocode criterion, is higher than that required based on the proposed criterion.

For such cases, both the proposed criterion in this study and that presented by Eurocode EN 1993-1-9 are capable of considering the positive effect of addition of stiffness by the strengthening system. Non-prestressed strengthening can be more effective for the members with small dimensions. However, as mentioned before, for riveted members with big dimensions, addition of non-prestressed material for strengthening doesn’t significantly increase the stiffness. At the end, it is quite case-dependent which option is the most economic.

4.3. Variable amplitude (VA) loading

Let’s assume that the riveted member shown in Fig. 4-a is subjected to an arbitrary VA loading. Using the Rainflow counting technique(Matsuishi and Endo, 1968, Shigley, 2011), the stress cycles can be categorized into the separate blocks. According to Eurocode(2005), for fatigue design of members under VA loading conditions, if the stress ranges in all blocks are lower than the CAFL, it is assumed that no fatigue damage is generated in the member. Otherwise, a bilinear S-N curve is used to model the development of the fatigue damage, and finally, to obtain the remaining fatigue life in the members.

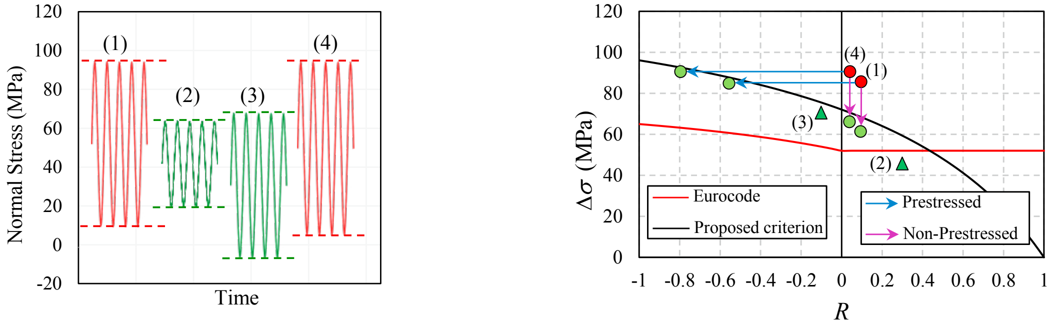
Each of the stress blocks represents a point in the $R-\Delta\sigma$ plot, like that shown in Fig. 3. Therefore, if the point corresponding to *i*th group of the blocks is below the CAFL, one may assume that no damage develops in the member. Otherwise, in order to achieve the infinite fatigue life, the member has to be strengthened either by prestressed or non-prestressed retrofitting systems.

In order to show the applicability of the proposed method for the fatigue design under VA loading, let's assume that the riveted member shown in Fig. 4-a is going to be subjected to new loadings (due to any reason); i.e. VA loading with four different blocks as given in Table 2, and, no damage has been already developed in the member.

Table 2. VA loading information

Stress block	R	Stress Range (MPa)	Max. Stress (MPa)	Min. Stress (MPa)
(1)	0.1	85	94.4	9.4
(2)	0.3	45	64.3	19.3
(3)	-0.1	75	68.2	-6.8
(4)	0.05	90	94.7	4.7

The stress blocks and the points related to each stress block in the $R-\Delta\sigma$ plot are given in Fig. 6. As shown in Fig. 6-b, stress blocks (1) and (4) are in the risky zone, while stress blocks (2) and (3) are below the proposed threshold, and therefore, don't generate alone (i.e. if not linked with blocks like 1 or 4) any damage to in the riveted member. In order to prevent any damage developing in the member, the stress blocks (1) and (4) have to be shifted inside the safe zone.



(a) Stress blocks

(b) $R-\Delta\sigma$ for different criteria

Fig. 6. Stress blocks in VA loading

When a prestressed strengthening system is used, the required prestressing forces of P_1 and P_4, shown in Fig. 6-b, are calculated using to Eq. (23), resulting in $P_1 > 334$ kN and $P_4 > 441$ kN .Therefore, for the design purpose, the prestressing force required to ensure that no fatigue damage developing in the member is $P_{\text{Design}} > \max.\ (P_1, P_4) = 441\ \text{kN}$.

For non-prestressed retrofitting systems, based on the proposed criterion, the required section modulus $(S^*_{\text{net}})_1$ and $(S^*_{\text{net}})_4$, in order to bring the points (1) and (4) in Fig. 6-b, respectively, into the safe zone is obtain using Eq. (24); $(S^*_{\text{net}})_1 > 20189355.1\ \text{mm}^3$ and $(S^*_{\text{net}})_4 > 20784804.6\ \text{mm}^3$. For the design, the required section modulus is: $(S^*_{\text{net}})_{\text{Design}} > \max.\ ((S^*_{\text{net}})_1, (S^*_{\text{net}})_4) = 20784804.6\ \text{mm}^3$. Following the same procedure, based on Eurocode criterion, the required section modulus $(S^*_{\text{net}})_{\text{Design}} > 31745806.4\ \text{mm}^3$ which is 50 percent higher than that needed based on the proposed criterion. At the end, to provide such section modulus, the designer has to determine the material (Young's modulus) and the cross section required to be added to the member.

4.4. Discussion on the remaining fatigue life estimation under VA loading

The proposed method is recommended not to be used for determination of the finite fatigue life N_f. That's because the proposed method originates from the CLD approach which is a local approach, and, in this method, the fatigue life is the defined as the number of cycles at which the fatigue cracks initiate. However, in the S-N curves presented in different codes of practice, the fatigue life is defined as the number of cycle at which the fatigue crack is detected; e.g. when the fatigue crack comes out of the rivet head.

Therefore, although even under VA loading, the CAFL can be calculated by the proposed method, but the calculation of the damage, which requires the calculation of N_f, has to be done based on the S-N curve proposed in Eurocode EN 1993-1-9 (2005) or any other codes for riveted members.

5. Conclusions

The major conclusions drawn from this study are summarized as follows:

- Research has demonstrated that the fatigue resistance is depending on the stress ratio. The existing codes are not effectively considering the effect of stress ratio on the CAFL value for riveted members. This makes it impossible to take into account the positive effect of stress ratio reduction when prestressed retrofitting systems are used on riveted members.
- An analytical model was proposed to introduce a criterion for the CAFL in riveted members. This method which accounts for the effect of stress ratio, originates from the CLD method as a local approach for the fatigue analysis. Contrary to the existing codes, the proposed criterion can be used for the design of prestressed retrofitting systems in riveted members. In addition, using the proposed criterion, design of non-prestressed strengthening systems becomes less conservative.
- Existing experimental data on fatigue of riveted members were collected. It was found that the existing criteria recommended for Eurocode as well as DIN and Austrian standard ÖNORM are conservative in the stress ratios smaller than 0.4. This leads to overdesigned non-prestressed strengthening systems.
- The proposed CAFL value was derived according to the considered experimental results, and, certain configurations. Therefore, further evaluation is needed for the cases of single lap joints, joints with a small number of rivet rows, and joints with corrosion.
- A design procedure was presented for the calculation of the prestressing force required for the prevention of fatigue crack using prestressed retrofitting systems, and, for the calculation of the required section modulus in non-prestressed strengthening systems.
- The proposed procedure for the design of strengthening systems was shown to be applicable for the constant and variable amplitude loading conditions.

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